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EMISSION OF FLARES IN THE X-RAY REGION OF THE SPECTRUM

by

A. S. Dvoryashin

L. S. Levitskiy

A. K. Pankratov

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by A. S. DVORYASHIN
L. S. LEVITSKIY
A. K. PANKRATOV

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A B S T R A C T

World data on the ionosphere (f_{min}) bursts of radio emission in the centimeter band and on chromospheric flares are used. The study of the connection between time characteristics (time of commencement, maximum and termination) of X-ray radiation and radio emission of flares, and characteristics obtained from observations in the optical region of the spectrum showed that the time dependences of X-ray radiation and radio emission practically coincide. However, the flare emission in H_{α}, commences prior to the time of intensity increase of these phenomena.

From the comparison of the minimum reflection frequencies f_{min}, registered during ordinary and proton flares, a considerable increase in the intensity of X-ray radiation from protons flares is found.

A large hardening of the X-ray radiation spectrum of the intense proton flares of March 23, 1958 and July 14, 1959 was detected. Assuming that additional ionization in the ionosphere originates at heights

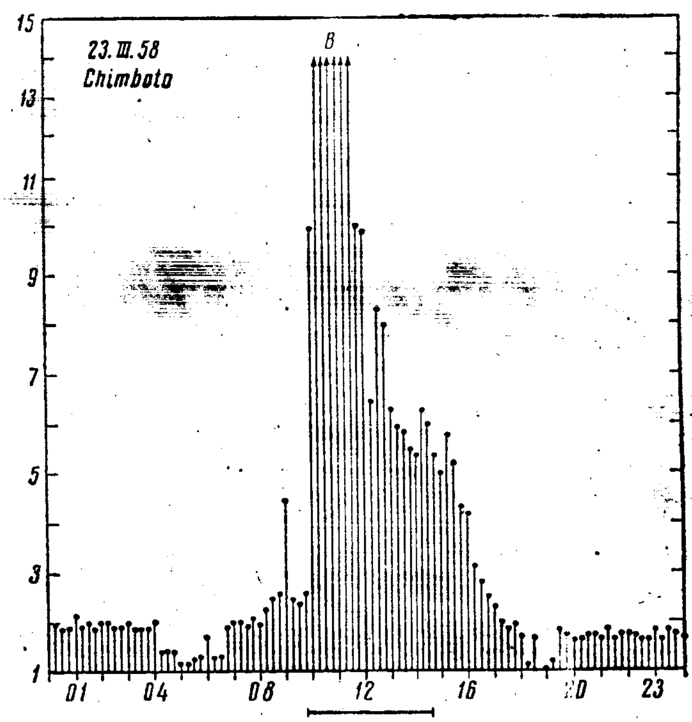
of 60 kilometers (for radiation's tangential incidence to the D-layer) it is concluded that super-hard protons with energies up to ~ 1 MeV should be generated during the development of intense proton flares.

Authors

1. INTRODUCTION.

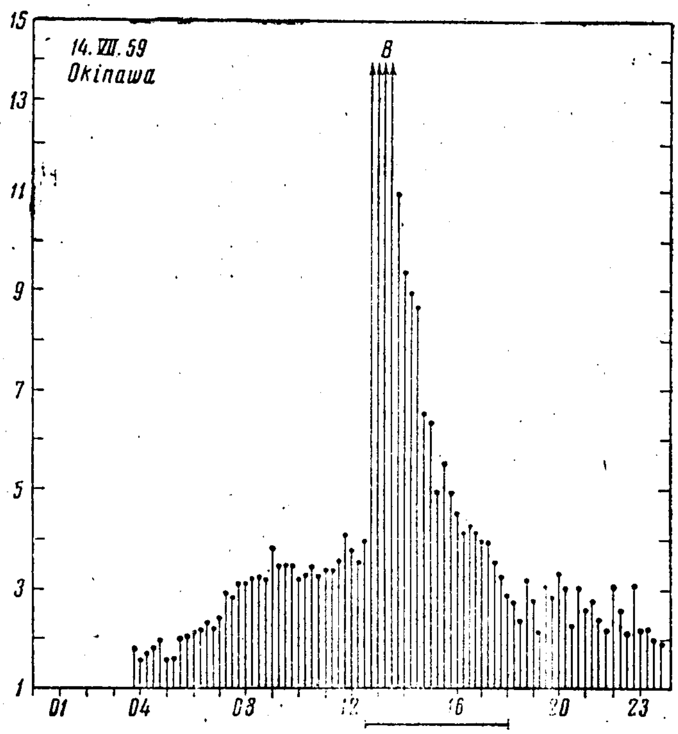
It has been revealed in references [1, 2, 3] that in a series of cases the development of chromospheric flares on the Sun is attended by the generation of high-energy protons ("proton flares"), whose energy spectrum extends at times to relativistic energies [4]. It has been established [5], that proton flares are accompanied by a powerf type IV radioburst, which characterizes to a significant extent the effectiveness of high-energetic particles' generation in the flare. According to [6], two or three phases may distinguished in the course of type IV burst development, everyone of which being due to the mechanism of electrons' synchronous radiation [7] with energies $E \sim 10^5 \div 10^8$ eV. The close correlation found between radio emission bursts and the absorption at high latitudes [5] points to the fact that the highly-energetic electrons, responsible for the type IV burst, or the synchronous radiation accelerate in the same active region as do the high-energy protons, settling at high geomagnetic latitudes. It is natural to expect that part of electrons may escape along the field from the emitting volume into denser layers of the chromosphere and into the photosphere. Consequently, the generation of X-ray quanta by electron brehmstrahlung accelerated in the flare is possible. At the same time, the number of generated photons and their hardness will be determined by the number

of accelerated electrons and their energies. For a given magnetic field, the intessity and the spectrum of radiobursts attending the flare, will be determined by the same quantities. Thus, one may anticipate that the powerful proton flares and the accompanying them type IV radiobursts in the centimeter band, must be attended by the generation of an intense flux of X-ray radiation (Fig.1), whose hardness is so much the greater, that the energy of electrons, accelerated in the flare, is higher. For the nonproton flares, the strength of radiobursts is considerably lesser, and accordingly, the intensity of X-ray radiation is significantly lower (Fig.2).



a

Fig.1. (a, б, в). Typical examples of f_{min} rise, conditioned by proton flares. During the development of the flare of 3 July 1957, two nodes and correspondingly, two separate radiobursts were observed in H_α
The trait below the graphs indicates the duration of the flare.



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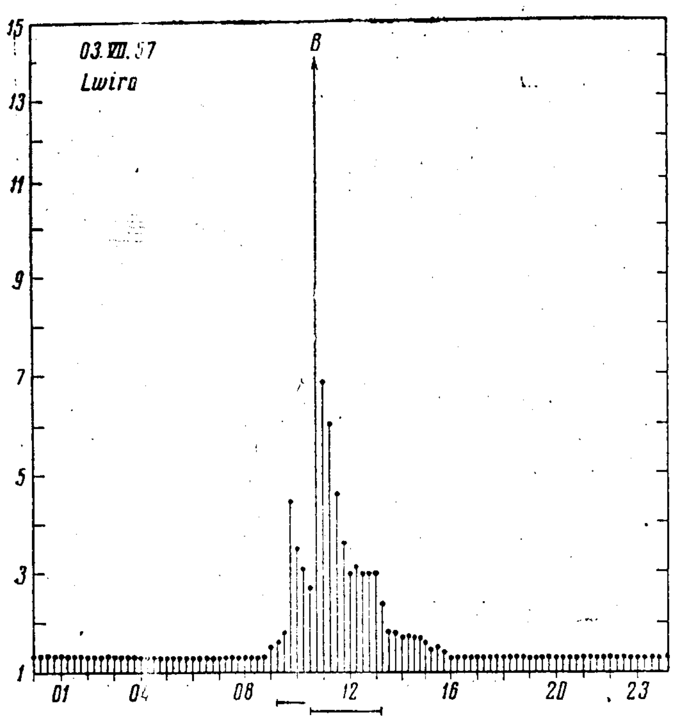

в

Captions for the above Fig.1 б and в, are in the preceding page.

2. METHOD OF INVESTIGATION OF X-RAY RADIATION.

By increasing the ionization of the lower ionosphere, the X-ray emission of the flares provokes a complex series of geophysccal phenomena, designated as sudden ionospheric disturbances (SID), — sudden increase in the level of atmospheric interferences (SEA), sudden phase anomalies in the propagation of long radiowaves (SPA), sudden increase in cosmic noise absorption (SCNA), shortwave absorption (SWF), increase in the minimum reflection frequencies f_{min}, total radiowave absorption during the vertical sounding of the ionosphere, and so for. A significant cycle of works by the Crimean Astrophysical Observatory [8 — 14] is devoted to the investigation of these phenomena. However, this research was carried out according to data of only one station.

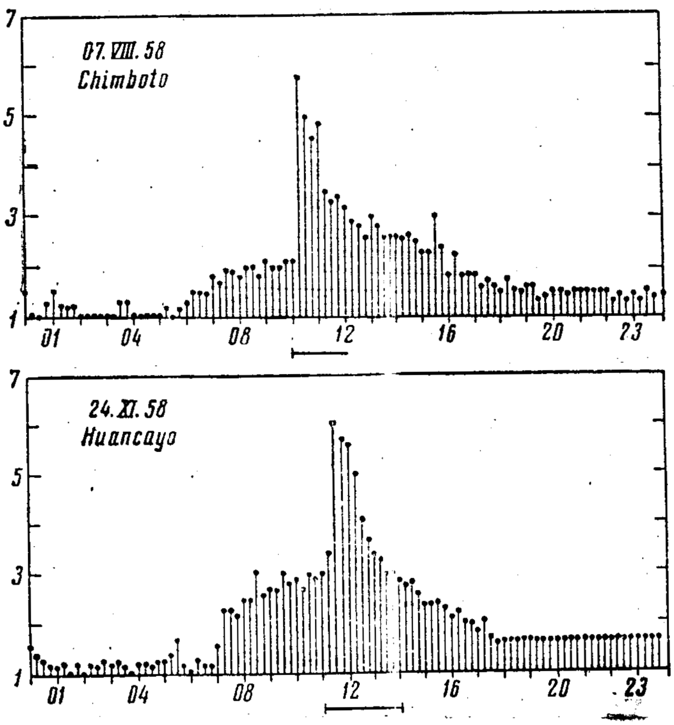

Fig. 2. Typical examples of f_{min} rise, conditioned by nonproton flares. The trait under the graph indicates the duration of the flare.

It is proposed in the current work to apply a method of investigation of flare X-ray emission, based upon the use of data on the minimum reflection frequencies f_{min}, obtained at the world network of ionospheric stations. For the instant of every chromospheric flare several stations may be located, for which the local time will be different, and consequently, the path followed by the radiation in the Earth's atmosphere will not be identical.

The radiation incident on the D-layer along the tangent (low position of the Sun above the horizon) will traverse an incomaparbly greater atmosphere thickness than that, incident perpendicularly (near the point under the Sun). Since the weakening of the X-radiation flux in passing the Earth's atmosphere along an identical path depends on the hardness of that radiation, a greater weakening shall be experienced by the flux of lower-energy photons. Consequently, the rise of f_{min} (or the total absorption in the ionosphere), registered at stations, sufficiently remote from the point under the Sun (low position of the Sun above the horizon), will be basically due to a harder radiation, for the soft component is "outfiltered" earlier by the Earth's atmosphere layers lying higher. Therefore, taking into account that a different kind of X-ray radiation weakeneing will take place at various portions of the spectrum during its passing the Earth's atmosphere, we may consider the latter as a peculiar filter, allowing the passing of harder and harder radiation as it gets deeper in the Earth's atmosphere. The advantage of such approach in the investigation of the X-ray radiation is quite evident. First of all, the pos-

possibility arises of comparing the effects of separate flares under identical condition of radiation registration, for example, by selecting stations near the subsolar point. Secondly, the investigation of the amplitude of the effects at various longitudes provides the possibility of estimating the relative hardness of the X-ray radiation for different flares. Thirdly, the investigation of f_{min} at stations sufficiently remote from the subsolar point, allows to ascertain the temporal course of the hardest X-ray emission for the corresponding flare. Obviously, the investigation of temporal course of the intensity and hardness of X-radiation, and also a more precise definition of the relationship of these characteristics with the course of flare and radioburst development are of utmost importance for the understanding of physics of nonstationary processes taking place in the active regions of the Sun.

3. OBSERVATION DATA.

The data on class 3 and 3+ chromospheric flares, utilized in the current work, were borrowed from reference [15]. Amongst class 2+ flares, only the proton flares were included in the work. (see [1, 2]). Information on 9400 mc/s radiobursts were borrowed from the Table in [5], & also from [16]. The utilized data on minimum reflection frequencies f_{min} at vertical soundings of the ionosphere, were obtained on the world network of ionospheric stations for the period IGY — IGC.

4. TEMPORAL RELATIONSHIP OF THE FLARE, THE RADIOBURST IN THE CENTIMETER BAND AND X-RADIATION

To investigate the mutual relationship between the chromospheric flare, the radioburst in centimeter wavelengths and the X-ray radiation, it is important to know the tempral sequence of these phenomena. As a first step in this research, we represented in Fig. 3 the commencement, the maximum and the duration of the flare, of the radioburst at 9440 mc/s and minimum reflection frequencies f_{min} for each of the cases studied. The moments of the maximum are plotted by vertical traits. If the commencement or termination moments of either event are unknown, this is indicated by dots. The moment of f_{min} rise is taken as the starting point of time count. It is plotted by solid vertical line. Still another dotted line is traced to the left, which is 15 minutes behind the former. Inasmuch as the values of f_{min} in the graphs, obtained according to IGY-IGC programs over the world station network, are only provided every 15 minutes, it may be said for any case, that the X-radiation flux is sufficient for the formation of a noticeable complementary ionization in the D-region, and that it would have reached the Earth not later than 0 h. and not earlier than 15 minutes, i.e. at some instant between vertical lines. Despite this shortcoming, we may draw a series of conclusions from the study of all cases brought out in Fig. 3, on the relationship between the flare, the radioburst and the emission in the X-ray band.

1) As a rule, a radioburst in centimeter wavelengths corresponds to increased values of f_{min}. Among class 3 flares, only that of 9 May 1959 was not attended by a radioburst. It must be stressed that neither was the f_{min} rise linked with that flare.

2) The moment of f_{min} increase follows much better the commencement of the burst in centimeter wavelengths, than the flare (see for example, 26 Sept. 1957, 24 November 1958, 4 August 1958, 26 August 1958, 1 February 1959).

3) Apparently, the moment of f_{min} increase coincides with the commencement of the radioburst in the centimeter wavelengths. The following facts may be brought forth as a corroboration of the above: One may see from Fig. 3 that the time of burst commencement is nearly always included between two vertical lines (0h—15 min). For certain bursts, commencement time coincides exactly with the moment of ionosphere sounding (carried out every 15 minutes), or otherwise, the burst begins near it. As may be seen in Fig. 3, the f_{min} rise is already observed at the moment of burst commencement (11 Sep. 1957, 3 July 1957, 24 July 1957, 26 September 1957, 20 October 1957, 29 July 1958, 30 September 1957, 31 December 1958). Since the f_{min} rise never begins earlier than the time of burst commencement, one may assert, that the generation and the egress of X- and radio emission of the flare take place practically simultaneously.

The time lag in f_{min} rise relative to the burst, observed at times, may be explained by the fact, that the intensity of X-radiation at the instant of burst commencement is low to induce a notable rise of f_{min},

while radio emission, even of low intensity, is registered by ground devices. As an example, we may indicate the flares of 14 July 1959, 29 November, 18 September 1957, 24 November 1958. 3 September 1957, 12 February 1959, 7 August 1959, 4 August 1958, 19 September 1957, 21 September 1957, when radioburst commences at the moment of ionosphere sounding. The f_{min} rises are not observed at all stations, as this was to be expected in case of an intense burst. However, for most of the cases, and because of the low X-radiation intensity, the f_{min} rise was apparently only registered at separate stations. A radioburst of exceptionally low intensity accompanied the flare of 20 November 1957 (cl. 3+). In that case, the rise of f_{min} becomes noticeable only at the maximum of the flare and of the burst.

4) Comparison of the commencement time of the flare and of the radioburst shows (Fig. 3) that the flare's commencement is nearly always ahead of that of the burst in centimeter band. As an average, the burst lags by about 6 minutes relative to the flare, but in many cases the retardation reaches $\sim$ 20 minutes.

5) With the exception of seven cases (18 and 26 Sep.1957, 12 Feb. 1959, 16 July, 2 Feb. 1959, 10 Sep. 1957, 5 March 1958), the time of the flare's maximum does not differ by more than $\pm$ 9 minutes from that of the burst maximum, but in many cases this difference is considerably smaller (See Table 1). As an average and considering all cases, the radioburst's maximum outstrips that of the flare by 0.8 min. (by 0.4 min., without the indicated seven cases). One may apparently assert that both,

the maximum of the flare and that of the radioburst occur simultaneously, or practically so, while the divergence, observed at times, which is of the order of $\pm$ 5 min., may be related to the errors in the determination of the time of the flare's and radioburst's maxima.

6) The time of the f_{min} maximum is indicated in Fig. 3 only for those flares, when it can be determined unilaterally. One may see that in all those cases, the maximum of f_{min} closely coincides with those of the flare and of the burst.

7) The comparison of the durations of the flare, the burst and of the increased f_{min} shows that in most cases, the flare has the longest duration. The duration of increased values of f_{min} coincides with that of the flare or is lesser. However, there are a series of flares (23 March 1958, 16 July, 12 February 1959, 31 August 1957, 26 Aug. and 29 July 1958), whose duration is less than that of increased f_{min} values. All of them are related to proton flares.

It must be noted that the time determination of the termination of the increased values of f_{min}, are the least reliable, for f_{min} decreases are in most of the cases rather smooth. Presented is in Fig. 3 the reliable maximum duration of f_{min}, determined by those low-latitude stations, for which the flare took place near noontime (local time). Let us also note, that the lesser duration of increased f_{min} values is apparently conditioned by the fact that, as the flare's glow in H_α attenuates, the intensity of X-radiation drops to a level insufficient for the formation of notable complementary ionization in the D-region.

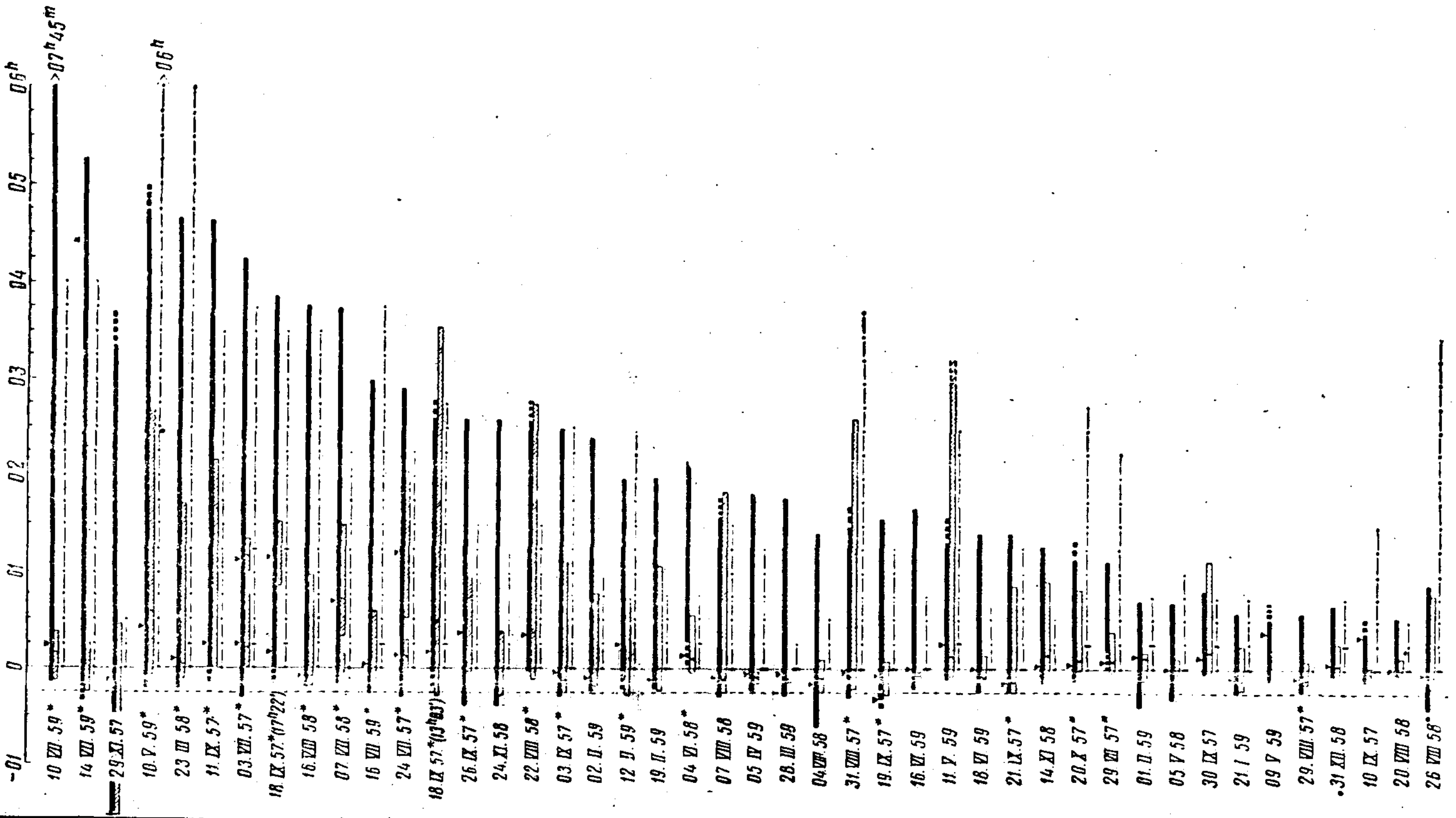

Fig. 3. Temporal link of the flare, and of the radioburst in the centimeter band with the X-ray radiation: ▬ — flare; ▨ — radioburst; —·—·— f_{min}

▼— flare maximum (vertical traits indicate radioburst and f_{min} maximum.) Proton flares are marked by stars.

Indeed, measurements carried out with the aid of rockets have shown [17], that the X-ray radiation of increased intensity persisted during some time after the H_α glow practically went out.

TABLE 1

Date	Difference between the maxima of the flare & of the burst in minutes	Date	Difference between the maxima of the flare & of the burst in minutes
3.VII 1957	+3 (9400 mc/s)	29.VII 195	0 (9400 mc/s)
	−1 (9400 mc/s)	4.VIII 19.	−4 (9400 "
24.VII 1957	+1 (9400 mc/s)	7.VIII 19.	+1 (9400 "
29.VIII 1957	+1 (9400 mc/s)	16.VIII 19.	0 (9400 "
31.VIII 1957	−3.5 (2800 mc/s)	20.VIII 19.	+1 (9400
3.IX 1957	+5 (9400 mc/s)	22.VIII 19.	−1 (9400
10.IX 1957	+22 (9400 mc/s)	26.VIII 19.	+1 (9400
11.IX 1957	−5 (9400 mc/s)	14.XI 1958	−6 (9400
18.IX 1957 (1303)	−5 (2800 mc/s)	24.XI 1958	+1 (2800
18.IX 1957 (1722)	+15 (2800 mc/s)	31.XII 195.	+1 (2800
19.IX 1957	+4 (9400 mc/s)	21.I 1959	+1 (2800
21.IX 1957	−1 (9400 mc/s)	1.II 1959	+1 (9400
26.IX 1957	+13 (2800 mc/s)	2.II 1959	−46 (2800
30.IX 1957	−4 (2800 mc/s)	12.II 1959	-12 (9400
16.X 1957	0 (9400 mc/s)	28.III 1959	+2.7 (9400
20.X 1957	−4 (2800 mc/s)	5.IV 1959	+4 (9400
29.XI 1957	+5 (9400 mc/s)	10.V 1959	−9 (9400
5.III 1958	+40 (9400 mc/s)	11.VI 1959	+8 (2800
23.III 1958	+3 (3000 mc/s)	16.VI 1959	+2 (9400
5.V 1958	0 (9400 mc/s)	18.VI 1959	+6 (9400
4.VI 1958	+2 (9400 mc/s)	10.VII 1959	+6 (9400
7.VII 1958	−1,8 (9400 mc/s)	16.VIII 1959	-34 (9400

As to the radio emission burst, its duration is less than that of the flare and of the increased values of f_{min}, as may be aeen from Fig.3. However, it must be stressed, that Figure 3 presents data on the duration of the flare only at 9440 mc/s (and at 2800 mc/s in some cases). As a rule, radiobursts in centimeter wavelengths are observed during longer times (see for example Fig.4; this question will be examined in detail in a separate work.

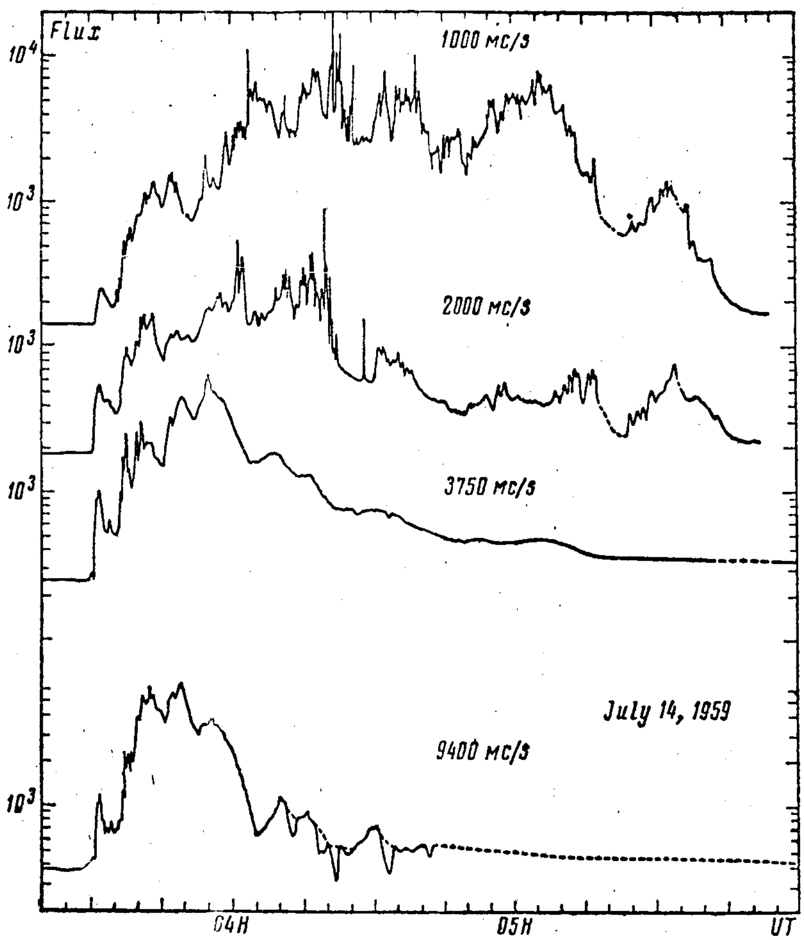

Fig. 4. Radioburst of 14 July, 1959 according to [23].

TABLE 2

LMT / h, км	13.VII 1959 станция Kihei		13.VII 1959 Rarotonga	23.III 1958 Buenos Aires	23.III 1958 станция Singapore	
	$18^h\,45^m$ $Z=85°19'$	$19^h\,00^m$ $Z=88°35'$	$17^h\,00^m$ $Z=88°04'$	$6^h\,15^m$ $Z=87°04'$	$18^h\,00^m$ $Z=87°6'$	$18^h\,15^m$ $Z=90°51'$
60	$m = 2.9$ г $\lambda_{10} = 0.60$ Å(21 KeV) $\lambda_e = 0.30$ Å(32 KeV)	6.1 0.41(30) 0.15(83)	5.3 0.45(28) 0.20(62)	4.6 0.49(25) 0.25(50)	4.1 0.51(24) 0.29(43)	16.0 0.10(124) 0.12(1030)
70	$m = 0.67$ $\lambda_{10} = 1.06(11.7)$ $\lambda_e = 0.80(16)$	1.4 0.82(15) 0.58(21)	1.2 0.85(14.6) 0.63(20)	1.1 0.89(14) 0.65(19)	0.97 0.93(13) 0.68(18)	4.0 0.52(24) 0.30(41)
80	$m = 0.11$ $\lambda_{10} = 2.00(6.2)$ $\lambda_e = 1.50(8.3)$	0.24 1.53(8.1) 1.14(10.9)	0.21 1.60(7.8) 1.20(10.3)	0.18 1.70(7.3) 1.25(9.9)	0.16 1.77(7.0) 1.31(9.5)	0.70 1.05(11.8) 0.78(16)
90	$m = 0.015$ $\lambda_{10} = 4.0(3.1)$ $\lambda_e = 2.9(4.3)$	0.032 3.0(4.1) 2.2(5.6)	0.028 3.2(3.9) 2.4(5.2)	0.024 3.4(3.6) 2.5(5.0)	0.022 3.5(3.5) 2.6(4.8)	0:10 2.06(6.0) 1.55(8.0)

5. HARDNESS OF IONIZING RADIATION

The hardness of ionizing radiation for two powerful proton flares of 23 August 1958 and 14 July 1959 was estimated by the method of mass determination of an inclined air column, expounded in ref [18], and making use of the atmosphere model brought out in references [19, 20]. Plotted are in Fig.5 the f_{min} diagrams for these flares obtained at the Singapore (01°19' N 103°49' E) and Kihei (20° 50'N 156° 30'W) stations, for which the zenithal angle of the Sun at those moments of time was near 90°. Masses of an inclined air column of 1 cm^2 cross-section, which must cut across the ionizing radiation from the flare in order to penetrate to 60, 70, 80 and 90 km altitudes above ground, are presented in Table 2 for the corresponding moments of time. The wavelengths in Å are brought out under the mass, and in parentheses — the corresponding quantum energy in keV. These weaken 10 and "e" times respectively, when passing through the given air mass. Presented are also in Table 2 similar data according to Barotonga (S 21° 12' W 159° 46') and Buenos Aires (S 34° 36' W 58° 29') stations, at which f_{min} increase (by 0.6 and 3.5 mc/s respectively) was also noted. The moments of time, for which zenithal angles were determined, are close to the moments of these flares' maxima.

The significant rise of f_{min}, provoked by these flares, and observable at the moment when the Sun is on the horizon, attests to the fact that a strong hardening of the spectrum constitutes a peculiarity of the X-radiation of these flares. The flare of 14 July 1959 is one of

the most powerful proton flares. The radioburst in the 9400 mc/s connected with it, reached in the maximum 7×10^{-19} w/m^{2}c/s. The maximum flux of highly-energetic protons, measured in the stratosphere, constituted 17 600 protons/cm^{2}sec [21].

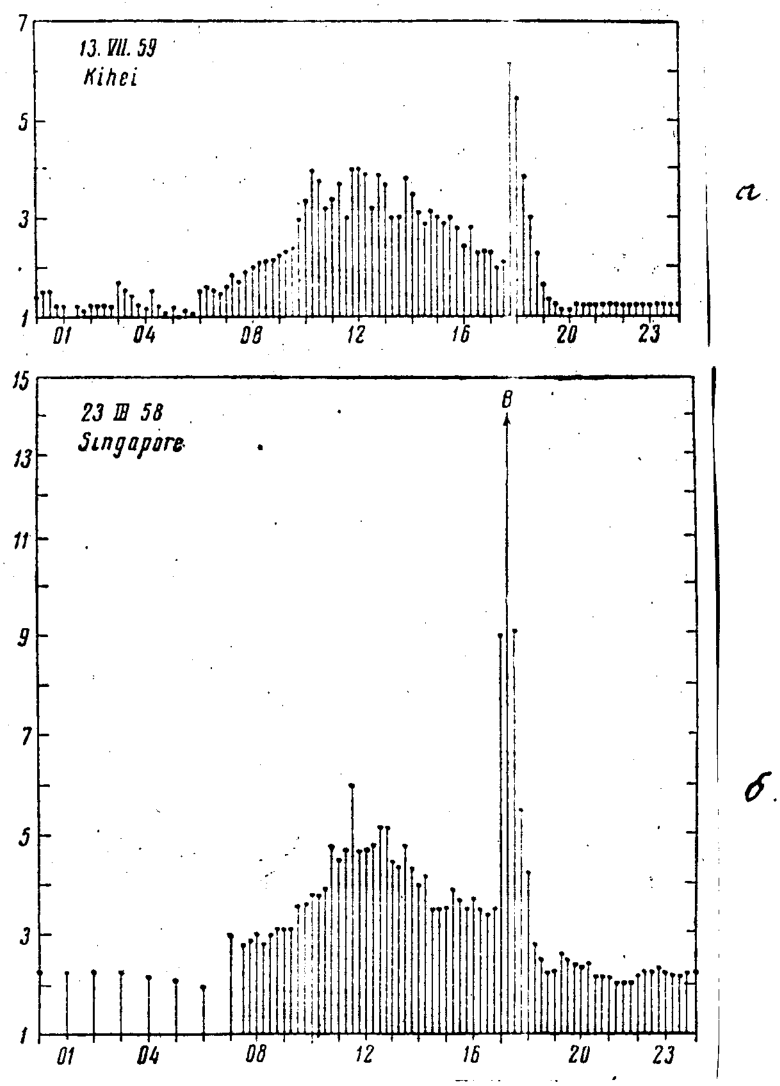

Fig. 5 a, б. Rise of f_{min} for great zenithal angles of the Sun, conditioned by hard X-ray radiation during powerful proton flares.

Rocket investigations, carried out during the moments of time near the sunrise or sunset, have shown [18], that the X-ray radiation of notable intensity is only registered at altitudes below ~ 90 km, which closely coincides with the basis of the E-layer. Consequently, in order to induce a notable f_{min} rise or a total absorption, the ionizing radiation must penetrate to a great depth. If we admit that the complementary ionization of the ionosphere caused by these flares, forms only at 60 — 70 km altitude, we may conclude that these flares were generated superhard photons with energy E ~ 0.1 MeV. The appearance of fluxes of quite hard X-ray quanta with energies of tens and hundreds KeV is revealed with the help of rockets, whose launchings were carried out during the time of class 2+ flares [22]. It is natural, that one may expect of powerful proton flares a more significant flux of hard photons, sufficient for the formation of notable complementary ionization of the D-layer at great zenithal angles.

In conclusion, the authors express their gratitude to V. V. Gapeyev for his assistance in the preparation for priniting of the experimental material.

***** E N D *****

Crimean Astrophysical Observatory
of the
USSR Academy of Sciences.

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